Kinematics and Stability Analysis of a Novel Power Wheelchair When Traversing Architectural Barriers

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Background: Electric-powered wheelchairs (EPWs) are essential devices for people with disabilities for mobility and quality of life. However, the design of common EPWs makes it challenging for users to overcome architectural barriers, such as curbs and steep ramps. Current EPWs lack stability, which may lead to tipping the EPW causing injury to the user. An alternative Mobility Enhancement Robotic Wheelchair (MEBot), designed at the Human Engineering Research Laboratories (HERL), was designed to improve the mobility of, and accessibility for, EPW users in a wide variety of indoor and outdoor environments. Seat height and seat inclination can be adjusted using pneumatic actuators connected to MEBot's 6 wheels. **Method:** This article discusses the design and development of MEBot, including its kinematics, stability margin, and calculation of the center of mass location when performing its mobility applications of curb climbing/descending and attitude control. Motion capture cameras recorded the seat angle and joint motion of the 6 wheel arms during the curb climbing/descending process. The center of mass location was recorded over a force plate for different footprint configurations. **Results:** Results showed that the area of the footprint changed with the location of the wheels during the curb climbing/descending and attitude control applications. The location of the center of mass moved ±30 mm when the user leaned sideways, and the seat roll and pitch angle were 0° and ±4.0°, respectively, during curb climbing and descending. **Conclusion:** Despite the user movement and seat angle change, MEBot maintained its stability as the center of mass remained over the wheelchair footprint when performing its mobility applications. **Key words:** *assistive technology, center of mass, stability, wheelchair control*

An electric-powered wheelchair (EPW) is a key mobility device for people with disabilities, providing independence, mobility, and a higher quality of life.[1] Currently, over 400,000 Americans benefit from using an EPW,[2] and this number continues to increase.[3] However, there have been limited improvements in EPW design to meet the increasing needs of users for expanded indoor and outdoor mobility over the past 20 years.[4] Notable improvements have been the inclusion of passive suspension[5] to decrease vibration, power seat functions, and expanded intuitive user interfaces.[4] Despite these improvements, accessibility and safety have been a challenge for commercial EPWs due to their limited mechanical design to overcome architectural barriers such as curbs[6,7] and steep ramps noncompliant with Americans with Disabilities Act of 1990 (ADA) standards in cross slopes (2° maximum) and ramps (5° maximum).[8] Driving through environmental barriers has led to wheelchair accidents such as tipping, which in some cases has led to hospitalization.[6,7,9]

All-terrain wheelchairs are often designed with 4 wheels[10] or track systems[11] for driving over difficult terrain and outdoor environments. Other robotic wheelchairs, such as the Wheelchair.q,[12] the wheelchair developed at the University of La Castilla-La Mancha,[13] the wheelchair developed at Nagasaki University,[14] and RT-Mover,[15] use wheel-legged mechanisms for the same purpose.

Advanced prototype EPW design such as the iBOT3000 incorporated indoor and outdoor mobility applications including 2-wheel self-balancing in the fore-aft directions, going up and down steep ramps, and climbing steps.[16] The users required good upper extremity strength and the ability to shift their center of gravity to climb steps.

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The TopChair is a climbing EPW only available in the European market that includes a track under the base that is activated only during a climbing sequence or when increased traction is required.[17] This feature, however, makes the wheelchair heavier than standard EPWs.

Several researchers have developed EPWs with the ability to successfully overcome architectural barriers such as curbs and steep ramps; however, these applications cause the EPW to have a large footprint, limited turning ratio, and decreased driving performance. In addition, these EPWs have limited capability to accommodate the physical impairments and mobility goals of EPW users for everyday use, such as powered seating functions and alternative controls.

The Mobility Enhancement Robotic Wheelchair (MEBot), designed in the Human Engineering Research Laboratories (HERL), was designed to address the limitations in EPW design and provide better maneuverability in both indoor and outdoor terrains. MEBot is a novel EPW that utilizes pneumatic actuators to maintain the seat height and orientation to reduce the risk of tips and falls and enhance its indoor/outdoor capabilities.[18] This article will describe the kinematics, stability analysis, and location of center of mass during the performance of 2 MEBot mobility applications: the curb climbing/descending application and attitude control application.

Methods

Description of the MEBot wheelchair

MEBot is a novel robotic EPW comprised of a 6-wheel design and an EPW seating system with powered seat functions. The characteristics of MEBot are shown in **Table 1**. The front and rear wheel casters are controlled via 4 independent pneumatic actuators mounted to the main frame. Two PMDC-powered wheels (80ZY24-350D-B; Linix, China) are mounted to the frame via a vertical-horizontal sliding platform, which allows the drive wheels to be moved fore and aft relative to the frame and up and down independently with pneumatic actuators in parallel with gas springs.[18] Pneumatic actuators are supplied by an onboard air tank through an air manifold. The electronic design of the MEBot wheelchair is divided into 2 controllers. The mobility control uses an R-NET wheelchair controller (Curtis-Wright, PA) to control the speed and direction of the drive wheels, while the manipulation control uses an open-loop control that allows manual adjustment of the seat height and inclination via switches. The manipulation control is comprised of a dsPIC33EP512 microcontroller

Table 1. Characteristics of the Mobility Enhancement Robotic Wheelchair and ANSI/RESNA wheelchair standards test results

Section 5: Overall dimensions	Dimension		Highest ground clearance		Lowest ground clearance	
	Length		1150 mm		1300 mm	
	Width		665 mm			
	Turning diameter		1250 mm		1670 mm	
	Ground clearance		241 mm		38 mm	
	Required corridor width for side opening		Entering	760 mm	990 mm	
			Exiting	760 mm	1140 mm	
	Wheelchair mass		414 lb			
Drive wheel horizontal movement	203 mm					
Power	24V, 51Ah					
Maximum velocity	5.0 mph (2.23 m/s)					
Section 1: Static stability	**Direction**				**Passive**	**Active**
	Forward				30.8°	28.4°
	Rearward				50.7°	---
	Sideways	**Left**			25.8°	37.7°
		Right			27.5°	36.3°

(Microchip, AZ) and a set of H-bridges, LM18200, used as interface between the switches and the air manifold to control the direction of each pneumatic actuator at full speed.

Kinematics and stability margin

To analyze the stability of the system, the location of the center of mass and its position relative to the wheelbase were calculated for different angles of the chair while the seat level was maintained. The calculations were based on the following assumptions:

- The wheelchair is stationary or slowly driving up, down the slope, and on cross slopes.
- The wheelchair is in front-wheel drive.
- Rear casters and drive wheels are co-planar with the ground.

To determine the position of MEBot's center of mass relative to the original flat reference frame, the difference angle between the actual pitch and roll values and the true orientation of the wheelbase relative to the frame must be calculated. To calculate the current pitch and roll values of the seat, the local coordinates of the wheels in the wheelchair's reference frame must first be calculated using the kinematics equations in **Figure 1A**:

$$RL = [nx + rcb * cos(rca), -rcy, nz - rcb * sin(rca)] \quad \text{Eq.1}$$

$$RR = [nx + rcb * cos(rca), rcy, nz - rcb * sin(rca)] \quad \text{Eq.2}$$

$$ML = [mx + dwb * cos(dwa), -dwy, mz - dwb * sin(dwa)] \quad \text{Eq.3}$$

$$MR = [(mx + dwb * cos(dwa), dwy, mz - dwb * sin(dwa)] \quad \text{Eq.4}$$

Where *RL*, *RR*, *ML*, and *MR* are the Cartesian coordinates of the left caster, right caster, and left and right drive wheel, respectively. *Nx*, *nz*, *mx*, and *mz* are the x-axis and z-axis location of each wheel arm's pivot point with respect to the origin point (0, 0) in the chair. Rca is the joint angle between the rear caster arm and the horizontal x-axis, and *dwa* is the angle between the drive wheel arm and the horizontal x-axis. Rcb is the length of the rear caster arm, and *Dwb* is the length of the drive wheel arm.

The orientation of the MEBot's wheelbase can be found by taking the cross product of the vectors between any 3 of its wheels. We choose the vectors between the wheelchair's right caster and right drive wheel and between its right caster and left drive wheel. Φ is the resulting pitch angle and θ is the resulting roll angle.

$$u1 = MR - RR;\ u2 = ML - RR;\ u = u1\ x\ u2 \quad \text{Eq.5}$$

$$\phi = -\tan^{-1}\left(\frac{u(1)}{u(3)}\right);\ \theta = -\tan^{-1}\left(\frac{u(2)}{u(3)}\right) \quad \text{Eq.6}$$

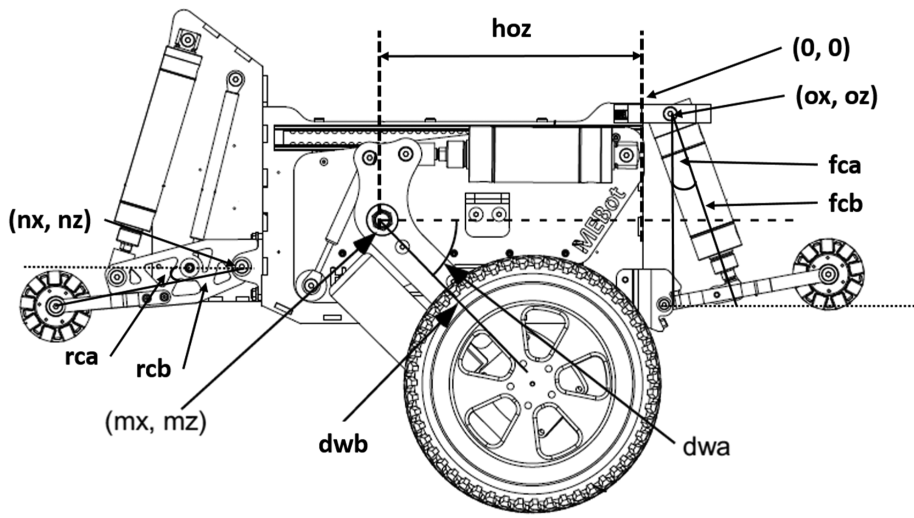

Figure 1. (A) Kinematics analysis of Mobility Enhancement Robotic Wheelchair (MEBot).

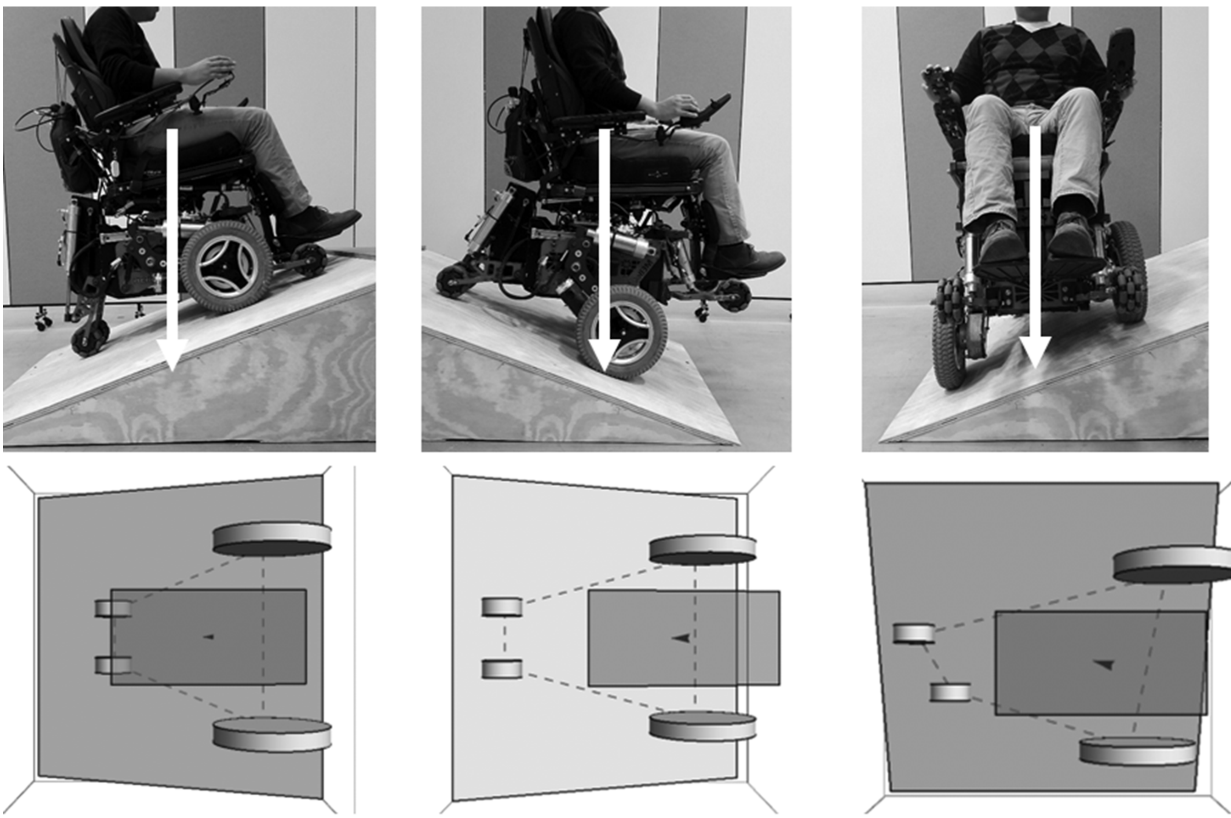

Figure 1. (B) Results of leveled seat and location of center of mass in tilt forward, tilt back, and lateral tilt when driving a 20° slope.

Determining the position of the center of mass over the ground plane requires calculating the difference between the wheelchair frame orientation and the pitch and roll values of the ground, *pin* and *rin*. The difference angle, *dphi* and *dtheta*, between the frame orientation and ground plane are shown below:

$$dphi = \phi + pin;\ dtheta = \theta + rin \qquad \text{Eq.7}$$

$$newcm = [cm\ (1,1) + cm(1,3)^*(dpi),\ cm(1,2) + cm(1,3)^*sin(dtheta),\ cm\ (1,3)^*(dpi)^*cos(dtheta) \qquad \text{Eq.8}$$

Prior to calculating the location of the center of mass in the simulation, the wheelchair was placed on a force plate (Bertec Corporation, OH), both flat and incline, to measure the actual position of the prototype's center of mass (cm1, cm2, cm3) (**Figure 3a**).

Returning to the simulation, *newcm* calculates the new location of the center of mass using the obtained angles about the wheelchair frame. To obtain the intersection of the center of mass with the ground plane, *s1* is used to account for the new orientation of the ground relative to the initial reference frame. *gg* gives the intersection point of the gravity vector extending downward from the center of mass with the ground plane.

$$ng = [sin(pin), sin(rin), cos(pin)^* cos(rin)] \qquad \text{Eq.8}$$

$$s1 = (ng.([0, 0, -5.5] - newcm))/(ng.[0,0,-1]) \qquad \text{Eq.9}$$

$$gg = s1^*\left[0, 0, -1\right] + newcm \qquad \text{Eq.10}$$

Results

Attitude control application

The attitude control application allows MEBot to manually keep its seat leveled when traversing over ramps and cross slopes. Driving in these uneven environments has been shown to cause shifts in the center of mass that lead to lack of stability EPWs.[4] This feature prevents tips and falls in these environments by detecting the inclination of the ground through a gyroscope-accelerometer sensor and moving the pneumatics actuators to a desired position to maintain the seat as flat. In a previously published article, a self-leveling seat control algorithm was described and evaluated for a previous iteration of MEBot 1.0.[19] While the software algorithm remained the same, the geometry of the wheelchair changed as shown in **Figure 1A** and was tested in simulation.[20] Limitations such as a restricted range of motion and load-lifting capabilities were addressed in MEBot 2.0. The MEBot 2.0 prototype was tested to ANSI/RESNA standards[21,22] defined in Sections 1, 2, 5, 6, and 10 of ISO 7176 as shown in **Table 1**.

Section 1 of the ANSI/RESNA standards determines the static stability of EPWs by placing them on a tilting platform. MEBot was tilted in 4 directions: lateral left, right, backward, and forward direction. For each direction, the tipping angle was recorded when the platform tilted until the uphill wheels left the ground. Results showed a maximum angle of 27° on cross slopes without the controller activated and an improvement to 37° using the attitude control application. For upward slopes, the center of mass remained within the footprint at a 50° angle (maximum angle of the tilting platform) with the attitude control de-activated in front-wheel-drive mode. Even though the attitude control was not required to maintain stability in this test, its ability to keep the frame level up to 15° would greatly improve user comfort. No changes in stability were noted with and without the controller when the platform was tilted forward, simulating driving down the slope. Due to the kinematics of the mechanism shifting the drive wheels backward relative to the frame with increasing ground clearance, the distance between the center of mass's gravity vector and the front of the wheelbase is reduced when adjusting for downward slopes. Again, although it would not change the stability margin for these extreme slopes, the ability to keep the frame leveled on slopes up to 15° should improve user comfort.

Section 2 of the ANSI/RESNA wheelchair standards determines the dynamic stability of EPWs by driving them at maximum speed forward and reverse and turning in a slope of 0°, 3°, 6°, and 10° and suddenly stopping to test stability when brakes are applied. The scoring system quantifies as follow: 0 = full tip, 1 = stuck on anti-tip, 2 = less than 3 wheels remain on the test plane, and 3 = at least 3 wheels remain on the test plane at all times.[22] MEBot passed all the dynamic stability tasks with a score of 3 using the assistance of its wheels' height adjustments. It was shown that MEBot required the assistance of the front casters when driving down the 10° slope and in front-wheel-drive mode to increase its footprint and stability margin. Alternatively, the allocation of the drive wheels to rear-wheel-drive mode would optimize the stability of the system.

For this article, the location of the center of mass was calculated and evaluated when MEBot 2.0 was driven up, down, and across a 20° slope using the attitude control application as shown in **Figure 1B**. The wheelchair was driven by the researcher who weighed 81.6 kg. As part of the calculations, it was assumed the footprint consisted of the area between the rear casters and drive wheels when driving in front-wheel-drive mode.

The results showed that the center of mass remained within the footprint of the wheelchair during each task, even when the area of the footprint changed with the wheelbase because of the movement of each wheel to compensate for the seat angle adjustment. Driving down the slope showed insufficient stability, as it was likely to maintain fewer than 3 wheels on the ground when brakes were applied and the center of mass approached the front of the wheelchair footprint. To provide an extra safety feature during this configuration, the frame was lowered using the pneumatic actuators as well as the front casters to act as anti-tippers to provide 6 points of contact to the ground as demonstrated during the Section 2: Dynamic Stability test of the ANSI/RESNA wheelchair standards. The seat angle in this configuration was -6.6° without the use of the powered seating functions. By combining the results from the static stability, dynamic stability, and the center of mass calculation, the wheelchair shows high stability when using the attitude control application and minimum change in the seat angle except when driving down a slope.

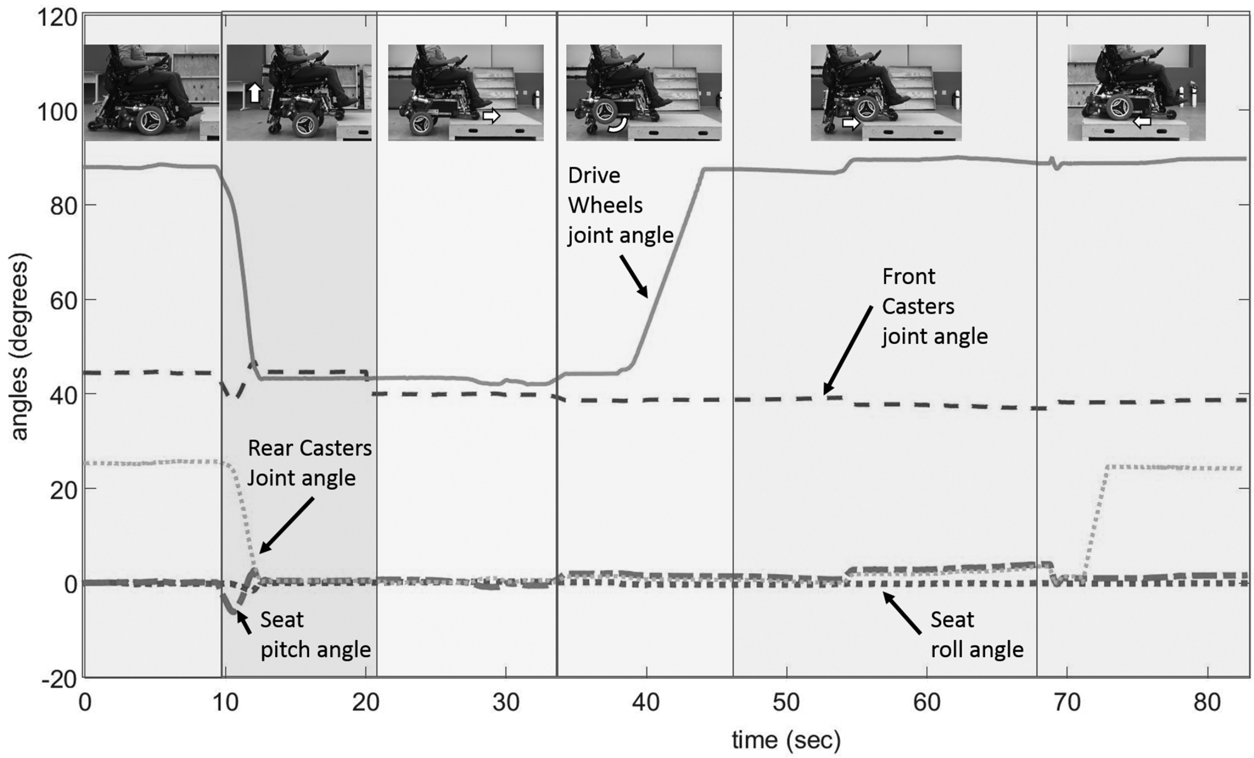

Figure 2. Curb-climbing sequence (top); angles of seat and wheel joints when ascending a curb (bottom).

Curb climbing and descending application

Accessibility remains a limitation for wheelchair users. Commercial power wheelchairs are rated to climb up to a 76 mm curb height facing perpendicular to the obstacle, otherwise the user is at risk of tipping.[23] In addition to the warning of this limitation, there is a lack of safety or adequate process when climbing or descending a curb. These criteria were considered when performing the application of curb climbing and descending. To provide safety and stability when curb ascending/descending, the application must follow the requirements and guidelines below:

- The center of mass must remain within the footprint of the wheelchair. In order to prevent tipping, the seat angle should maintain a horizontal level or must not pass the maximum tilting angles obtained in the Section 1 test of the ANSI/RESNA wheelchair standards.
- The wheelchair should be able to climb/descend a maximum curb height of 203.2 mm. Section 10 of the ANSI/RESNA wheelchair standards determines the ability to climb and descend obstacles of EPWs, which can be varied in height from 10 mm to a height of 200 mm.

During testing of the curb-climbing function, the wheelchair was manually controlled by the researcher. To demonstrate the kinematics of the chair, the application was used to climb a curb height of 203.2 mm on a runway with 16 motion capture cameras to detect 24 reflective markers placed on the wheelchair at each corner of the seat, at each corner of the curb platform, at the center of each of the 6 wheels, and at each joint of the 6 pneumatics within the frame. The seat angle and each wheel joint motion were monitored at 100 Hz frequency and presented in **Figure 2**. The curb-climbing sequence consisted of 5 main steps:

1. When approaching the curb, the user elevates the wheelchair to the highest ground clearance in order to place the front casters on the curb. The ground clearance increases to 241 mm to overcome the maximum ADA curb height of 203.2 mm as stated in Section 10 of the ANSI/RESNA wheelchair

standards. The highest ground clearance configuration maintains the center of mass within the footprint without using the front casters as shown in **Figure 3b**. When the wheelchair elevates, the front casters move forward due to the mechanical design of the wheelchair to rise as a "scissor lift" and reach the top of the curb.

2. The frame moves forward to place the drive wheels on top of the curb. Two DC motors (BDWG319NP-207-24-45-FL-C6-W3; Anaheim Automation, CA) drive the horizontal carriage from front to back in 10 seconds. In this step, the wheelchair is in rear-wheel-drive mode with casters on the ground, increasing its stability margin as shown in **Figure 3b** and maintaining its center of mass in the center of the footprint.
2. Once the carriage is moved back, the drive wheels are elevated to clear the curb height, changing its joint angle from 43° to 85° as shown in **Figure 2**. In this configuration, the radius of the drive wheels is higher than the remainder of the curb height, and the wheelchair can drive over the curb. At this moment, the wheelchair is resting on its casters, keeping the center of mass in the center despite the reduction in the stability margin sideways as shown in **Figure 3c**.
3. The drive wheels move to front-wheel drive using the horizontal carriage. At the same time, the drive wheels spin and their brakes unlock to prevent them from getting caught on the edge of the curb.
4. The rear casters are elevated to drive all the wheels over the curb.

The curb-climbing sequence was completed in 75 seconds. The seat roll angle was 0° while the pitch angle read ±4.0° when the wheelchair was elevated to its highest ground clearance and when the drive wheels were on top of the curb. However, the wheelchair remained in a static posture during the entire process, and the wheelchair had 4 points of contact throughout the curb-climbing sequence. This, in combination with the results in the static stability test, demonstrated that the center of mass remained within the footprint of the chair.

A secondary test was performed on a force plate to locate the center of mass of the entire system (wheelchair plus user) for different footprint configurations in the curb-climbing process. During this test, the user leaned as far as possible for 5 seconds in the left and right directions when the wheelchair was static to demonstrate the stability of the system when the user moves in the seat, as shown in **Figure 3**. This stability test was limited to leaning sideways as the center of mass was closer to the sides of the wheelbase than the back or front in each configuration. The results showed a change of ±30 mm when leaning sideways, while remaining well within the footprint. For front-wheel-drive mode, it was observed that the highest ground clearance is the least stable configuration, as the center of mass is 81 mm closer to the front of the wheelchair than at the lowest ground clearance (**Figure 3b**). While the center of mass remained within the footprint, it is suggested that, depending on the mobility application, the front casters be lowered to increase the stability margin or the maximum speed be reduced to no more than 3.5 mph when driving in this configuration on a flat surface to prevent tipping.

The curb-descending sequence used the same requirements as when climbing a curb. The sequence was completed in 5 steps as shown in **Figure 4**:

1. The front casters are lowered on top of the curb to align the wheelchair perpendicular to the curb.
2. Once the front casters drop off the curb, the frame is moved forward while the front casters are lowered to the ground to maintain a footprint area.
3. Then, the wheelchair drives forward to lower the drive wheels to the ground. The wheelchair is in rear-wheel-drive mode in this step and the rear casters are lowered to the ground as well.
4. The drive wheels are moved forward to front-wheel-drive mode while front casters are elevated.
5. The wheelchair is lowered to its lowest ground clearance.

The seat roll angle remained completely flat while the pitch angle showed a ±5° change when the drive wheels moved from the curb to the ground and in the transition from highest to lowest ground clearance. The footprint configurations in the curb-descending process were similar to the curb climbing, which maintained the center of mass within its footprint.

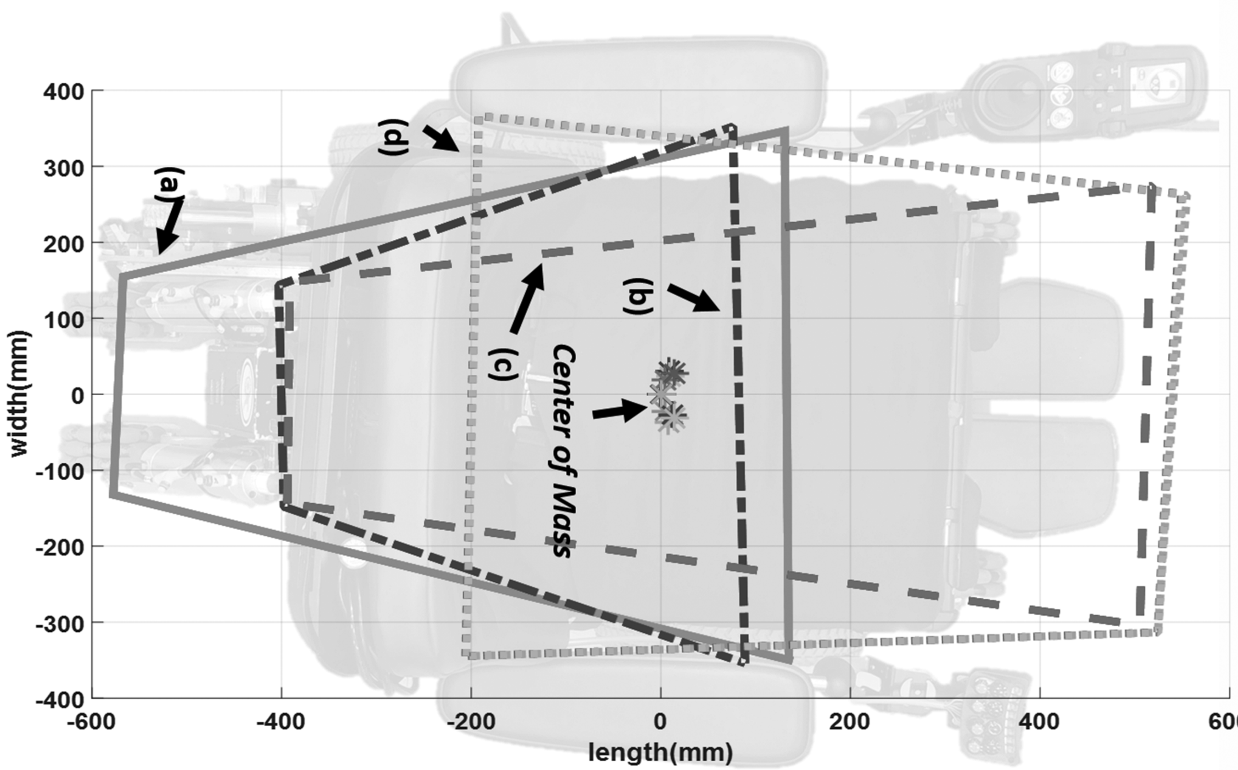

Figure 3. Location of the center of mass when climbing a curb in different footprint configurations: (a) lowest ground clearance, (b) highest ground clearance, (c) only front and rear casters on the ground, and (d) only drive wheels and front casters in rear-wheel drive.

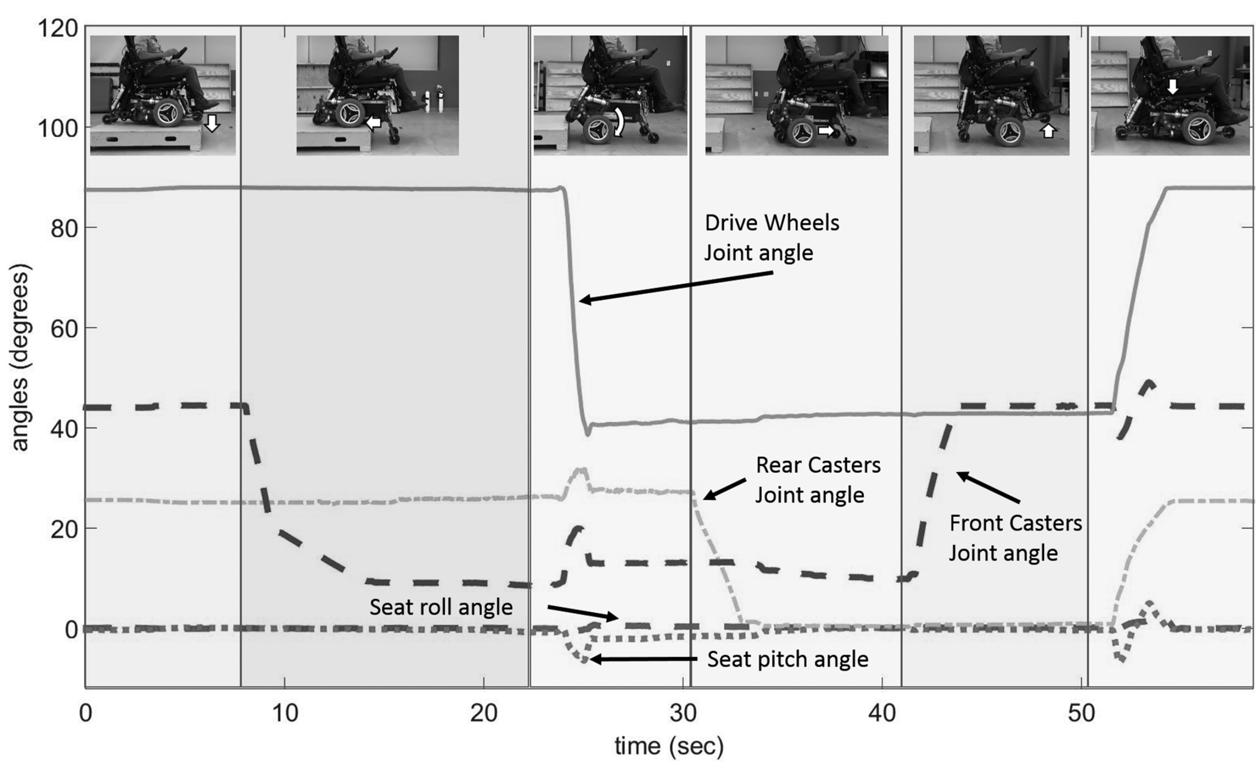

Figure 4. Curb-descending sequence (top); angles of seat and wheel joints when descending a curb (bottom).

Discussion

The mobility applications of the MEBot 2.0 – curb climbing/descending and attitude control – were introduced and evaluated through a stability analysis. The results showed that the position of the center of mass remained within the footprint of the wheelchair on slopes of different angles and while climbing and descending a curb. It was also discovered that the least stable configurations of the wheelchair were in high ground clearance and when driving down the slope in front-wheel drive. To compensate for instability, it was recommended that the front casters be used as anti-tippers. In addition, MEBot includes powered seating functions that can be used to adjust its seat inclination when driving up or down slopes up to 60°. Further work will include an optimization of the kinematics and attitude control algorithm in different wheel drive configurations and wheel height positions to maintain the level seat. Even though the completion time of the curb climbing/descending process was not the objective of the study, it could be improved with automation of each wheel motion in every step of **Figures 2** and **4**. However, the study demonstrated the capabilities and stability of MEBot when climbing over ADA-compliant steps (8 in. high) in comparison to commercial EPWs, which are limited to climb curb heights not exceeding 3 in. and lack safety when overcoming architectural barriers. The location of the center of mass can be obtained with the wheelchair angle and the position of the wheels. This equation can be used for further development of the automation and potential safety failure analysis of the mobility applications.

Acknowledgments

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